Updates from the “Gobal SMEFT Fit Team”

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Energy Frontier Workshop - Restart
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The energy frontier

- **Build large colliders $\rightarrow$ go to high energy $\rightarrow$ discover new particles!**

- Higgs and nothing else?

- What's next?
  - Build an even larger collider (~ 100 TeV)?
  - No guaranteed discovery!

The energy frontier

- **Build large colliders** $\rightarrow$ go to high energy $\rightarrow$ discover new particles!

  do precision measurements $\rightarrow$ **discover new physics indirectly!**

- Higgs and nothing else?

- What's next?
  - Build an even larger collider (~ 100 TeV)?
  - No guaranteed discovery!
  - **Higgs factory!** (A lepton collider at $\sqrt{s} \sim 240$-250 GeV or above.)
  - **SMEFT** (model independent approach)

Why lepton colliders?

- **Higgs (and Z, W, top) factory!**
  - Large statistics, clean environment
    $\Rightarrow$ **precise measurements!**
- EFT is good for lepton colliders.
  - A systematic parameterization of Higgs (and other) couplings.
- Lepton colliders are also good for EFT!
  - High precision $\Rightarrow$ $E \ll \Lambda$
    Ideal for EFT studies!
  - LHC is built for discovery, but ....

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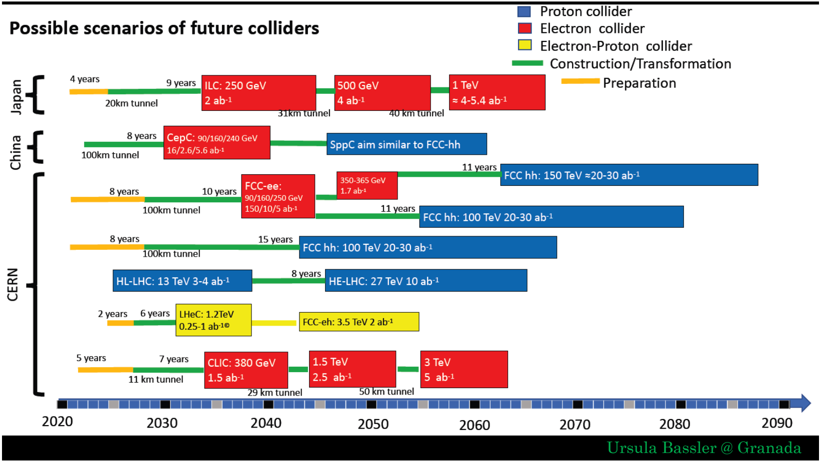
  - LHC is built for discovery, but ....
- **Energy** *vs.* **Precision**
  - Poor measurements at the high energy tails lead to problems in the interpretation of EFT...
    (See also Gauthier's talk.)

Possible timelines of future colliders



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- **Goals:**
  - ~~Produce some "official snowmass result" and then claim everyone else's result is wrong.~~
  - Prepare an illustrative global Higgs/EW fit for 1) future lepton collider results and 2) combinations of future hadron and lepton collider results.
  - Compare the capabilities of various future colliders on an equal footing. (Mission impossible?)
  - Understand the roles/impacts of different measurements (Z-pole, top-threshold, beam polarizations, *etc.*).
  - Understand the general issues, subtleties and limitations in the global fitting and the combinations of different measurements.

- **Anyone who would like to help is welcome to join!**

What has been done so far (for EFT global fits at future lepton colliders)

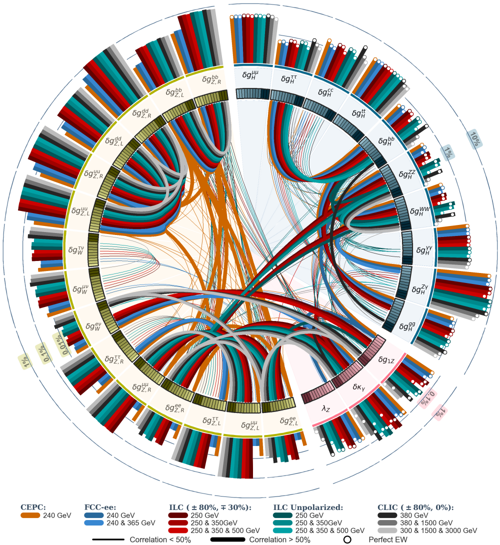
- Higgs + WW (assuming perfect Z-pole)
  - [1510.04561] Ellis, You, [1704.02333] Durieux, Grojean, Gu, Wang
- Higgs + WW + Z-pole
  - [1708.08912 & 1708.09079] Peskin *et al.* (ILC group)
  - [1905.03764] ECFA study, [1907.04311] de Blas, Durieux, Grojean, Gu, Paul
  - WW: Full EFT parameterization (beyond 3 aTGCs)
- Triple Higgs coupling at one loop
  - [1312.3322] McCullough, [1711.03978] Di Vita *et al.*
- Top EFT (threshold and above)
  - [1807.02121] Durieux, Perelló, Vos, Zhang, [1907.10619] Durieux *et al.*
- Top loops in Higgs and EW processes (RG running, full 1-loop contribution)
  - [2006.14631] Jung, Lee, Perelló, Tian, [1809.03520] G. Durieux, Gu, E. Vryonidou, C. Zhang

Global fit

- **Global fit**
  - Usually $\sim 20\text{-}30$ parameters (instead of 2499) if we focus on Higgs and electroweak measurements.
- **Limits on all the $\frac{c_i^{(6)}}{\Lambda^2}$**
  - Results depend on operator bases, conventions, ...
- **Or present the results in terms of effective couplings?**
  ([arXiv:1708.08912], [arXiv:1708.09079], Peskin *et al.*)
  - $g(hZZ)$, $g(hWW)$ couplings have multiple contributions: $hZ^\mu Z_\mu\,,\;\; hZ^{\mu\nu}Z_{\mu\nu}$ ...
    defined as: $g(hZZ) \propto \sqrt{\Gamma(h\to ZZ)}\,, \quad g(hWW) \propto \sqrt{\Gamma(h\to WW)}\,.$
  - Intuitive, can be interpreted as "Higgs couplings."
  - Gives you the illusion that you understand the results...
- **Present the results with some fancy bar plots!**

Fit Results

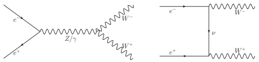
[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul

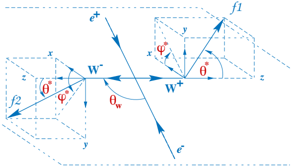


- Global fit of dim-6 operators at tree-level with Higgs and electroweak measurements.
- Correlations are also important!

$e^+e^- \to WW$ with Optimal Observables

- TGCs (and additional EFT parameters) are sensitive to the differential distributions!
  - One could do a fit to the binned distributions of all angles.
  - Not the most efficient way of extracting information.
  - Correlations among angles are sometimes ignored.



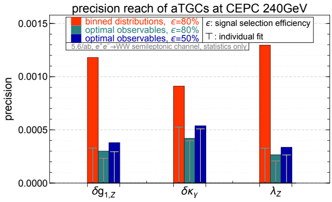


- What are optimal observables?

  (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - In the limit of large statistics (everything is Gaussian) and small parameters (linear contribution dominates), the best possible reaches can be derived analytically!

$$\frac{d\sigma}{d\Omega} = S_0 + \sum_i S_{1,i}\, g_i\,, \qquad c_{ij}^{-1} = \int d\Omega \frac{S_{1,i} S_{1,j}}{S_0} \cdot \mathcal{L}\,,$$

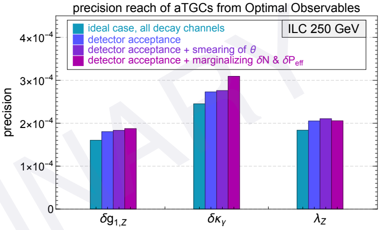
- The optimal observables are given by $\mathcal{O}_i = \frac{S_{1,i}}{S_0}$, and are functions of the 5 angles.

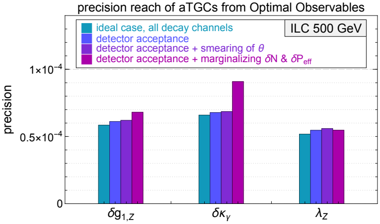


[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul

Updates on the *WW* analysis with Optimal Observables

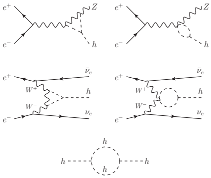
- How well can we do it in practice?
  - detector acceptance, measurement uncertainties, ...
- What we have done
  - detector acceptance
    ($|\cos\theta| < 0.9$ for jets, < 0.95 for leptons)
  - some smearing
    (production polar angle only, $\Delta = 0.1$)
  - ILC: marginalizing over total rate (δN) and effective beam polarization (δP_{eff})
- Constructing full EFT likelihood and feed it to the global fit. (For illustration, only showing the 3-aTGC fit results here.)
- Further verifications (by experimentalists) are needed.

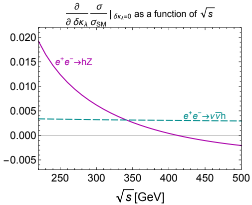


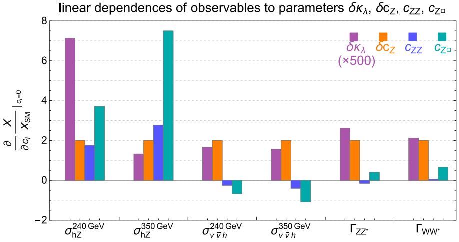


Triple Higgs coupling at one-loop order

[arXiv:1711.03978] Di Vita, Durieux, Grojean, JG, Liu, Panico, Riembau, Vantalon

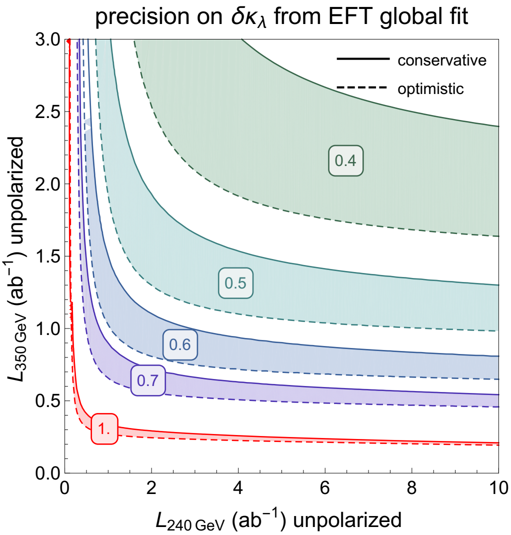






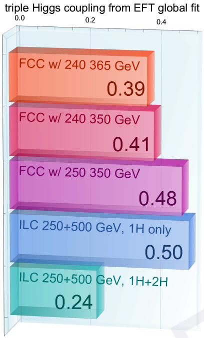
- $\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}$,
  $\delta\kappa_\lambda \equiv \kappa_\lambda - 1 = c_6 - \frac{3}{2}c_H$,
  with $\mathcal{L} \supset -\frac{c_6\,\lambda}{v^2}(H^\dagger H)^3$.
- One loop corrections to all Higgs couplings (production and decay).
- 240 GeV: hZ near threshold (more sensitive to $\delta\kappa_\lambda$)
- at 350-365 GeV:
  - WW fusion
  - hZ at a different energy
- $h \to WW^*/ZZ^*$ also have some discriminating power (but turned out to be not enough).

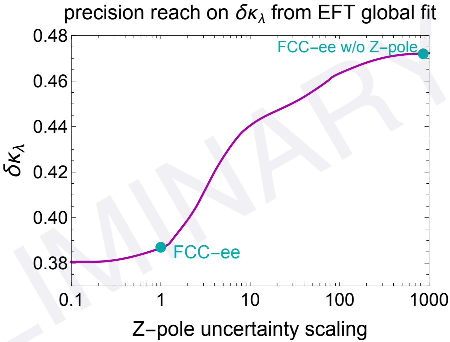
Triple Higgs coupling from EFT global fits



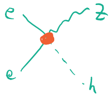
- Runs at two different energies (240 GeV and 350/365 GeV) are needed to obtain good constraints on the triple Higgs coupling in a global fit!

Updates on the triple Higgs coupling determination from EFT global fits





- 240, 365 GeV are better than 250, 350 GeV.
- Impacts of Z-pole measurements are not negligible. ($eeZ(h)$ contact interaction enters $e^+e^- \to hZ$.)



What's next?

- More (tree level) dim-6 operators?
  - 4-fermion operators ($e^+e^- \to f\bar{f}$), CP-odd operators ...
  - A global fit of all dim-6 operators with all measurements?
- More loop contributions of dim-6 operators?
  - Top-operator loops: Large degeneracy without higher energy runs?
  - Effects can be non-negligible even if the operators are constrained at tree level. (see *e.g.* [1909.02000] Dawson, Giardino)
- Beyond dim-6?
  - Dim-8 bases have been written down. ([2005.00008] Shu et al., [2005.00059] Murphy) Some analyses are available.
  - Many more free parameters?
  - Giving up power counting if we treat dim-6 and dim-8 on an equal footing?
- SMEFT *vs.* HEFT...
  - Non-SMEFT HEFT requires $v \sim \Lambda$?
- **We don't have to do everything at once!**

backup slides

$e^+e^- \to WW$ parameterization

- "~~Higgs~~ effective coupling basis"
  (+ deviations in W BR. δ_{m_W} is constrained very well by W mass measurements.)

$$\delta g_{1,Z},\ \ \delta\kappa_\gamma,\ \ \lambda_Z,\ \ \delta g^{ee}_{Z,L},\ \ \delta g^{ee}_{Z,R},\ \ \delta g^{e\nu}_{W},\ \ \delta_{m_W}$$

- ILC parameterization (projective map to any EFT basis)

$$e,\ \ g_L,\ \ g_R,\ \ g_Z,\ \ g_W,\ \ \kappa_A,\ \ \kappa_Z,\ \ \lambda_A,\ \ \lambda_Z,\ \ BR$$

- 2 nuisance variables δN, δP_{eff} for ILC
  - $e^+e^- \to WW$ is also used to determine the effective luminosity and polarization.

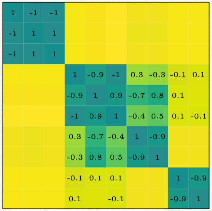
Top EFT

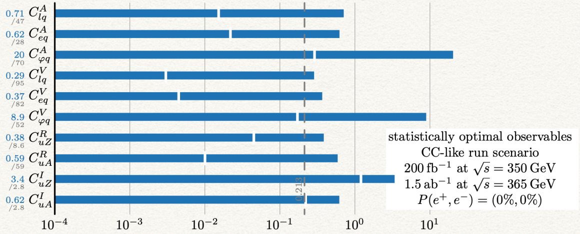
[arXiv:1807.02121] Durieux, Perelló, Vos, Zhang

$$
\begin{aligned}
O^1_{\varphi q} &\equiv \tfrac{y_t^2}{2}\ \bar q\gamma^\mu q\ \ \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, &
O_{uG} &\equiv y_t g_s\ \ \bar q T^A\sigma^{\mu\nu}u\ \ \epsilon\varphi^* G^A_{\mu\nu},\\
O^3_{\varphi q} &\equiv \tfrac{y_t^2}{2}\ \bar q\tau^I\gamma^\mu q\ \ \varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi, &
O_{uW} &\equiv y_t g_W\ \ \bar q\tau^I\sigma^{\mu\nu}u\ \ \epsilon\varphi^* W^I_{\mu\nu},\\
O_{\varphi u} &\equiv \tfrac{y_t^2}{2}\ \bar u\gamma^\mu u\ \ \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, &
O_{dW} &\equiv y_t g_W\ \ \bar q\tau^I\sigma^{\mu\nu}d\ \ \epsilon\varphi^* W^I_{\mu\nu},\\
O_{\varphi ud} &\equiv \tfrac{y_t^2}{2}\ \bar u\gamma^\mu d\ \ \varphi^T\epsilon\, iD_\mu\varphi, &
O_{uB} &\equiv y_t g_Y\ \ \bar q\sigma^{\mu\nu}u\ \ \epsilon\varphi^* B_{\mu\nu},
\end{aligned}
$$

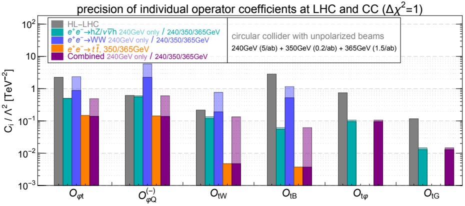
$$
\begin{aligned}
O^1_{lq} &\equiv \tfrac{1}{2}\ \bar q\gamma_\mu q\ \ \bar l\gamma^\mu l,\\
O^3_{lq} &\equiv \tfrac{1}{2}\ \bar q\tau^I\gamma_\mu q\ \ \bar l\tau^I\gamma^\mu l,\\
O_{lu} &\equiv \tfrac{1}{2}\ \bar u\gamma_\mu u\ \ \bar l\gamma^\mu l,\\
O_{eq} &\equiv \tfrac{1}{2}\ \bar q\gamma_\mu q\ \ \bar e\gamma^\mu e,\\
O_{eu} &\equiv \tfrac{1}{2}\ \bar u\gamma_\mu u\ \ \bar e\gamma^\mu e,
\end{aligned}
$$

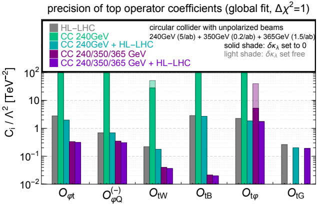
- Also need to include **top dipole** interactions and *eett* contact interactions!
- Hard to resolve the top couplings from $4f$ interactions with just the 365 GeV run.
  - Can't really separate $e^+e^- \to Z/\gamma \to t\bar t$ from $e^+e^- \to Z' \to t\bar t$.
  - Is that a big deal?

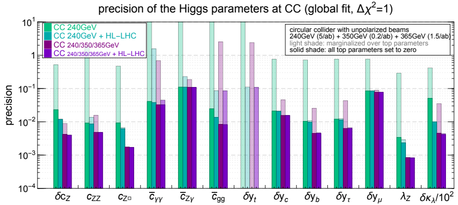


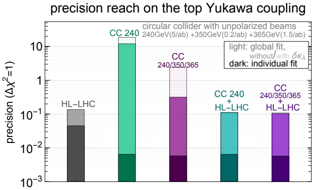


Top operators in loops [arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang





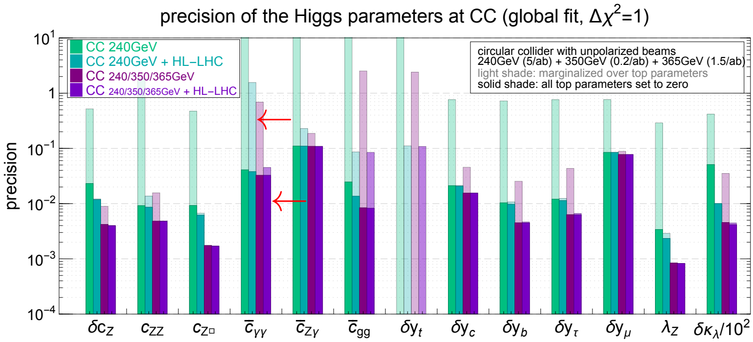




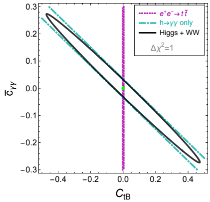
- Higgs precision measurements have sensitivity to the top operators in the loops.
  - But it is challenging to discriminate many parameters in a global fit!
- HL-LHC helps, but a 360 or 365 GeV run is better.
- Indirect bounds on the top Yukawa coupling.

Top operators in loops

[arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang

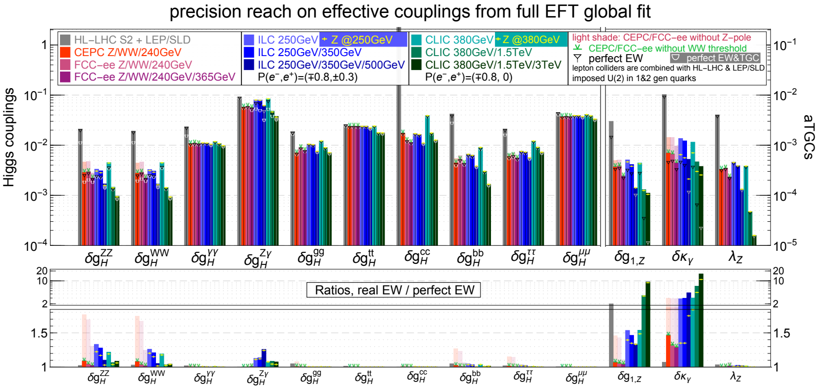


- $O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\varphi} B_{\mu\nu} + h.c.$ is not very well constrained at the LHC, and it generates dipole interactions that contributes to the $h\gamma\gamma$ vertex.
- Deviations in $h\gamma\gamma$ coupling $\Rightarrow$ run at ~ 365 GeV to confirm?



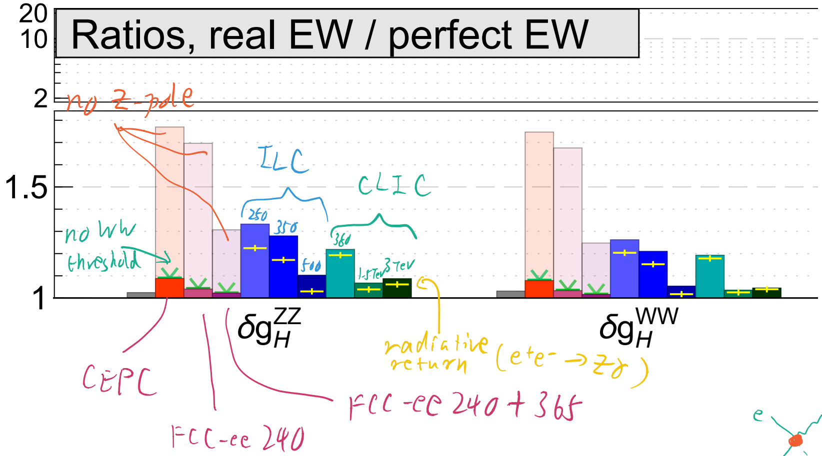
“Full fit” projected on the Higgs couplings (and aTGCs)

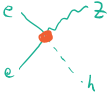
[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul, see also Higgs@FutureColliders WG report



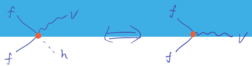
- 28-parameter fit, projected on the Higgs couplings & aTGCs.
- Lepton colliders are combined with HL-LHC & LEP/SLD.
- The *hZZ* and *hWW* couplings are not independent!

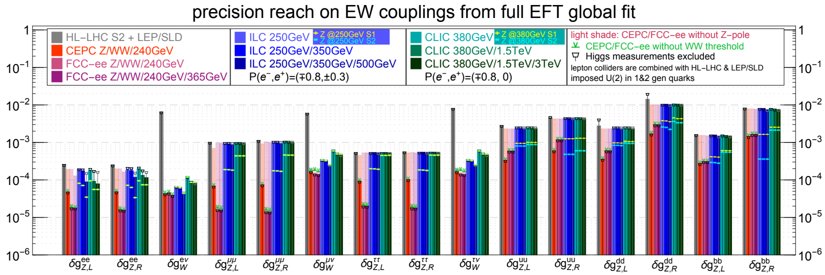
Z-pole run is also important for Higgs couplings!





Reach on the (h)Vff couplings





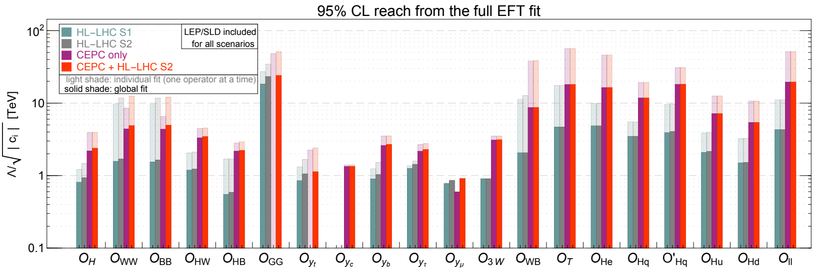
- $(h)Zff$ couplings are still best probed by future Z-pole runs.
- Higgs and diboson measurements at high energy (at linear colliders) are also sensitive to the $(h)Zee$ couplings, but can not resolve them from other parameters.
- Linear colliders: Using radiative return ($e^+e^- \to Z\gamma$) to measure Z observables at high energy?

D6 operators

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{q}_L H d_R + \text{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{l}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

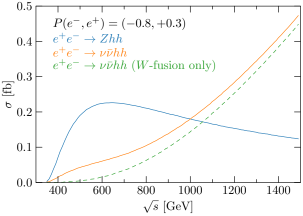
- SILH' basis (eliminate $\mathcal{O}_{WW}$, $\mathcal{O}_{WB}$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH' basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$)

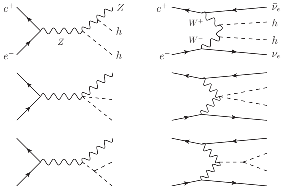
Reach on the scale of new physics



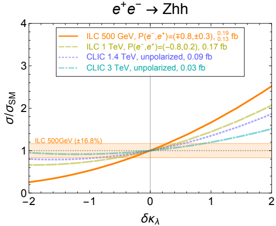
- Reach on the scale of new physics Λ.
- Note: reach depends on the couplings c_i!

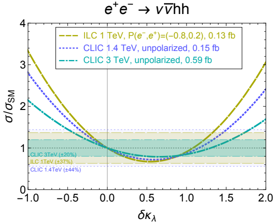
Double-Higgs measurements ($e^+e^- \to Zhh$ & $e^+e^- \to \nu\bar{\nu}hh$) [arXiv:1711.03978]

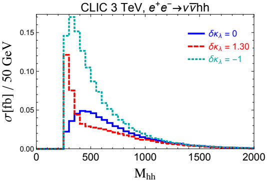




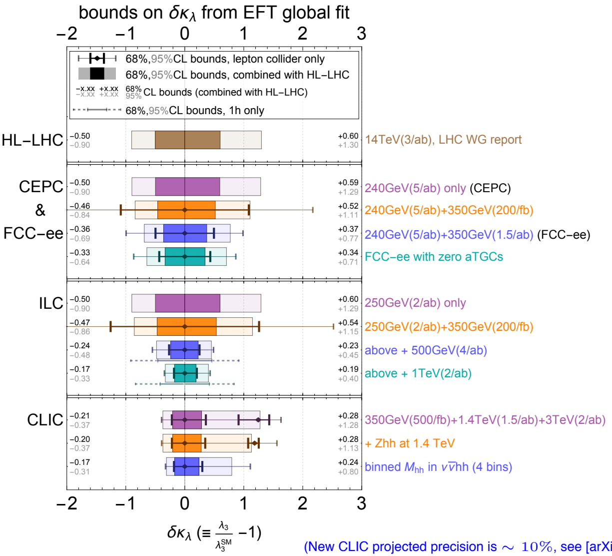
- Destructive interference in $e^+e^- \to \nu\bar{\nu}hh$! The square term is important.
- hh invariant mass distribution helps discriminate the "2nd solution."







Triple Higgs coupling from global fits [arXiv:1711.03978]



(New CLIC projected precision is $\sim 10\%$, see [arXiv:1901.05897] Roloff *et al.*)

Triple Higgs coupling (Higgs@FutureColliders WG, [arXiv:1905.03764])